U-boson and the HyperCP exotic events

Chuan-Hung Chen[1,2*], **Chao-Qiang Geng**[3†], **and Chung-Wen Kao**[4‡]

[1]*Department of Physics, National Cheng-Kung University, Tainan 701, Taiwan*

[2]*National Center for Theoretical Sciences, Hsinchu 300, Taiwan*

[3]*Department of Physics, National Tsing-Hua University, Hsinchu 300, Taiwan*

[4]*Department of Physics, Chung Yuan Christian University, Chung-Li 320, Taiwan*

(Dated: April 22, 2008)

Abstract

We show that the very light spin-1 gauge U-boson of the extra $U(1)'$ gauge model in the framework of the supersymmetric standard model extension can be a good candidate of the new light particle suggested by the HyperCP experiment. We demonstrate that the flavor changing neutral currents (FCNCs) for the HyperCP events in the decay of $\Sigma^+ \to p\mu^+\mu^-$ can be generated at both tree and loop levels. In particular, we find that the loop induced $s \to dU$ transition due to the tensor-type interaction with the dimension-5 electric dipole operator plays a very important role on the FCNCs. Our explanation of the HyperCP data with the spin-1 U-boson is different from that based on a light pseudoscalar Higgs boson or sgoldstino in the literature. In particular, the U-boson involves a rich phenomenology in particle physics as well as cosmology.

* Email: physchen@mail.ncku.edu.tw

† Email: geng@phys.nthu.edu.tw

‡ Email: cwkao@phys.cycu.edu.tw

An unexpected large branching ratio (BR) for $\Sigma^+ \to p\mu^+\mu^-$ has been measured to be $[8.6^{+6.6}_{-5.4}(\text{stat}) \pm 5.5(\text{syst})] \times 10^{-8}$ by the HyperCP experiment at Fermilab [1]. Due to the short-distance contributions being negligible, this "anomalous" result could just reflect the uncertain long-distance effects [2, 3]. However, the unforeseen result is actually based on three observed events, which all appear at the narrow range of the dimuon mass distribution in $\Sigma^+ \to p\mu^+\mu^-$. The probability for the three events arising from the form-factor decay spectrum in the standard model (SM) is estimated to be around 0.8% [4]. Therefore, a more accessible speculation is that a new neutral resonance, denoted by X^0, with mass of 214.3 ± 0.5 MeV has been produced through the decay chain $\Sigma^+ \to pX^0, X^0 \to \mu^+\mu^-$ and the corresponding BR is $\mathcal{B}(\Sigma^+ \to pX^0, X^0 \to \mu^+\mu^-) = [3.1^{+2.4}_{-2.9}(\text{stat}) \pm 1.5(\text{syst})] \times 10^{-8}$ [1].

To be consistent with the HyperCP events, this new particle is assumed to be light and weakly couple to the SM particles. Subsequently, several possible candidates for this new particle have already been suggested, such as a light pseudoscalar Higgs boson in the next minimal standard supersymmetric model (NMSSM) [5] and a light sgoldstino in some supersymmetric models [6]. In addition, a model-independence effective interactions via scalar, pseudoscalar, vector and axial vector currents have also been analyzed in Refs. [7, 8, 9]. In this study, besides giving a specific model to realize the conjecture on axial vector currents which have been studied by the model-independent approach, we will show that the tensor-type effective interactions missed in the literature are also important for the HyperCP data.

In the SM, the flavor changing neutral currents (FCNCs) are generated by quantum loops. Consequently, it is believed that due to the loop suppression and Glashow-Iliopoulos-Maiani (GIM) mechanism [10], the associated FCNC processes are usually sensitive to the new physics effects. It has been known that there exist many extensions of the SM, such as supersymmetric [11], left-right symmetric [12] and flavor-changing Z' [13, 14] models, which all involve new flavor structures and induce new FCNCs at loop and/or tree levels. After surveying the models in the literature, we find that the simplest extension of the SM, that could naturally provide a light spin-1 boson and axial couplings to the SM fermions, is the supersymmetrized $U(1)'$ gauge model.

It has been shown that a new neutral gauge boson associated with an extra $U(1)'$ gauge symmetry is a necessity to be responsible for the spontaneous supersymmetry breaking and the generation of large sfermion masses [15]. To distinguish from the normal Z'-boson,

here we use U-boson to represent the new gauge boson. Since the U-boson is regarded as the spin-1 superpartner of the massless spin-1/2 goldstino, its features include (a) axial and weak couplings to the fermions and (b) a very light mass [16]. The special characters of the U-boson as well as its related phenomenologies have been discussed extensively in Refs. [17, 18, 19, 20]. In addition, the studies of directly detecting the U-boson at BESIII and identifying it as X^0 can be found in Ref. [21]. As to other possible light gauge boson physics, one could refer to Refs. [22, 23]. In this paper, we are going to demonstrate that the spin-1 U-boson in the supersymmetric $U(1)'$ model could be the candidate of the new light particle X^0. In particular, we will show that the model provides the mechanism of FCNCs in $\Sigma^+ \to p\mu^+\mu^-$ for the HyperCP events at both tree and loop levels. We emphasize that the loop induced $s \to dU$ transition involves the electric dipole type of tensor interactions, which has not been investigated yet in the literature.

To make the model to be more concretely, we adopt the simplest approach proposed in Ref. [16], in which the theory is based on the framework of supersymmetry (SUSY) with $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'_X$ gauge symmetries. To get correct symmetry breaking, the model involves two Higgs doublets $H_{u,d}$ and one singlet N. Since the couplings between the U-boson and SM fermions are very weak, with the $\nu_\mu e$ scattering, the mass of the U-boson could be less than a few hundreds MeV. In our model, since the couplings of the U-boson to SM fermions are through axial vector currents, in order to make the model be anomaly free, it is necessary to introduce new heavy fermions with opposite $U(1)'$ charges to ordinary fermions. Moreover, the $U(1)'$ charges of quarks would be different for different generations like the nonuniversal Z' model [13, 14]. It should be noted that the fermion $U(1)'$ charges for the models in the literature [15, 16, 17, 18, 19, 20, 21] are generation blind and therefore, the U-boson in our discussion here should be viewed as a variation of the conventional U-boson in the literature. Nevertheless, the main features of the U-boson are the same.

To investigate the U-boson effects, we start by writing the interactions of the U-boson and fermions as

$$\mathcal{L}_{ffU} \; = \; -g_U \sum_f Q_f \left[\bar{f}_R \gamma_\mu f_R - \bar{f}_L \gamma_\mu f_L \right] U^\mu \,, \tag{1}$$

where g_U denotes the gauge coupling of $U(1)'$, Q_f is the $U(1)'$ charge for the corresponding particle and $f_{L(R)} = P_{L(R)} f$ with $P_{L(R)} = (1 \mp \gamma_5)/2$. As an illustration, we may take $Q_2 = -Q_1 = q$ and $Q_3 = 0$, where 1, 2 and 3 are the family index. In this simple toy model,

no more exotic fermions are needed as the $U(1)'$ related anomalies are cancelled among the first and second families and the Yukawa couplings are ok, while Eq. (1) is obtained. Of course, to have a realistic CKM mixings, a more complex Higgs structure is needed. From Eq. (1), since gauge charges are generation dependent, FCNC interactions can be generated by

$$g_U \bar{D}_i \gamma_\mu \left(V_R^D \mathbf{Q} V_R^{D^\dagger} P_R - V_L^D \mathbf{Q} V_L^{D^\dagger} P_L \right)_{ij} D_j U^\mu \,, \tag{2}$$

where D_i represents the physical eigenstate of the down quark, diag$\mathbf{Q}_i = Q_i$ and $V_{L(R)}^D$ are the unitary matrices for diagonalizing the down-type-quark Yukawa matrix Y^d. We note that the flavor number of down quarks in the anomaly-free model could be more than three. From the above result, it is clear that although Eq. (1) contains only axial couplings, due to the misalignment between V_L^D and V_R^D, in general the effective interactions of the U-boson and quarks have not only axial vector currents but also vector ones.

It has been known that without finetuning, the CP violating phases in models with SUSY bring a large effect on the neutron electric dipole moment (NEDM). To solve this CP problem, the Yukawa and SUSY soft breaking matrices could be considered as hermitian [24], *i.e.*, $Y^{d^\dagger} = Y^d$ and $A^{d^\dagger} = A^d$, respectively. Interestingly, the hermitian Y^d could be naturally realized in the extensions of the SM, such as left-right symmetric models [25]. Moreover, with hermitian Yukawa matrices, one can show that in the supergravity framework, A^d is nearly hermitian even after including renormalization group running effects [24]. Despite the origin of the hermiticity, if we adopt a hermitian matrix of Y^d, since $M_D^{dia} = V_L^D Y^d V_R^{D^\dagger}$, immediately we get $V_L^D = V_R^D \equiv V^D$. Accordingly, from Eq. (2) the FCNC for $s \to dU$ at tree level is found to be

$$\mathcal{L} \;=\; -g_U V_{12} \bar{d} \gamma_\mu \gamma_5 s U^\mu + h.c. \tag{3}$$

where $V_{12} = (V^D \mathbf{Q} V^{D^\dagger})_{12}$. Clearly, we successfully obtain the FCNCs at tree level in the specific model. Meanwhile, we find that when Yukawa matrices have the property of hermiticity, axially coupled effective interactions between the U-boson and quarks in the physical states are returned as Eq. (1). It should be an interesting problem to ask how reliable the hermitian Yukawa matrices are. Moreover, it is worth discussing about the mass matrices of quarks. It has been known that the determination of flavor mixing matrices $V_{L,R}^F$ (F=D, U) is governed by the detailed patterns of the mass matrices. In terms of data, the

CKM matrix, defined by $V_L^U V_L^{D\dagger}$, is approximately a unity matrix. Accordingly, the quark mass matrices are very likely aligned and have the relationship of $\mathcal{M}_D = \mathcal{M}_U + \Delta(\lambda^2)$ with $\mathcal{M}_{U(D)} = M_{U(D)}/m_{t(b)}$ [27, 28, 29], where λ is the Wolfenstein parameter. In Ref. [29], it showed that the Fritzsch quark mass matrices, given by [26, 28]

$$M_F = R_F \bar{M}_F H_F \text{ with } \bar{M}_F = \begin{pmatrix} 0 & A_F & 0 \\ A_F & 0 & B_F \\ 0 & B_F & C_F \end{pmatrix} \tag{4}$$

where R_F and H_F are diagonal phase matrices, could lead to reasonable structures for the mixing angles and CP violating phase in the CKM matrix just in terms of the quark masses. Interestingly, when $R_F = H_F^\dagger$, the simple Fritzsch mass matrices are hermitian. That is, although hermitian mass matrices of quarks are a subset of general cases, the simple patterns have brought us enough information for the flavor physics. Hence, in our following analysis we will adopt the assumption of hermiticity for the Yukawa matrices. We remark that the interaction in Eq. (3) can be easily extended to those with $b \to s$ and $b \to d$ transitions [8].

From Eq. (3), we aware that FCNCs at tree with the axial coupling for the $s \to d$ transition in the literature could arise from the nonuniversal supersymmetric $U(1)'$ model. In addition, because the interacting form of Eq. (3) is the same as that parametrized by the model-independent approach. We can take the procedure discussed in the Refs. [5, 7, 8, 9] to constrain the parameter $g_U V_{12}$. Consequently, if the events of the HyperCP data are regarded as the production of the resonance, with the narrow width approximation, the BR for $\Sigma^+ \to pU, U \to \mu^+\mu^-$ can be written as the product of $\mathcal{B}(\Sigma \to pU) \times \mathcal{B}(U \to \mu^+\mu^-)$. Since the anomalous events show up only in the dimuon mode, it is plausible to take $\mathcal{B}(U \to \mu^+\mu^-) \approx 1$. We remark that in general the U particle would also couple to the electron and neutrinos. In this case, as the experimental constraints on Eq. (3) from $K_L \to \ell\bar{\ell}$ $(\ell = e, \nu)$ are much weaker than $K_L \to \mu^+\mu^-$, our numerical results in the followings need to be simply rescaled. Hence, using Eq. (3) and the results of the Chiral Lagrangian for the $\Sigma^+ \to pU$ transition, by fitting the HyperCP data one easily finds that $|g_U V_{12}|^2 \approx (4.4^{+3.4}_{-2.7} \pm 2.1) \times 10^{-20}$ [7].

To take the interaction in Eq. (3) more seriously, we should examine whether other experiments will give a more stringent constraint on $g_U V_{12}$. It has been analyzed that in fact, except $\Sigma^+ \to p\mu^+\mu^-$, the most serious bound is from $K_L \to \mu^+\mu^-$ instead of the

$K^0-\bar{K}^0$ mixing [7, 8]. From the results in Ref. [8] and by adopting $\mathcal{B}(K_L \to \mu^+\mu^-) < 10^{-10}$, one obtains $|g_U V_{12}|^2 \Gamma(U \to \mu^+\mu^-) < 2.8 \times 10^{-30}$ with

$$\Gamma(U \to \mu^+\mu^-) \;=\; \frac{|g_U Q_\mu|^2 m_U}{12\pi}\left(1-\frac{4m_\mu^2}{m_U^2}\right)^{3/2}, \tag{5}$$

where Q_μ is the $U(1)'$ gauge charge of the muon. Fortunately, the unknown parameter $g_U Q_\mu$ can be directly constrained by the muon anomalous magnetic moment. Thus, the U-boson mediated muon $g-2$ can be calculated to be [20, 31]

$$\Delta a_\mu = \frac{g_\mu^2}{4\pi^2}\frac{m_\mu^2}{m_U^2} F_U\left(\frac{m_\mu^2}{m_U^2}\right)$$

with $g_\mu = g_U Q_\mu$ and

$$F_U(a) = \int_0^1 dz \frac{z(1-z)(4-z)+2az^3}{1-z+az^2}\,.$$

According to the current data, we know that the difference between the experimental value and the SM prediction is $\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (22 \pm 10) \times 10^{-10}$ [32]. Using $\Delta a_\mu < 10^{-9}$ and Eq. (5), the limit on the partial decay rate is given by $\Gamma(U \to \mu^+\mu^-) < 5.5 \times 10^{-12}$. Combining with the bound of $K_L \to \mu^+\mu^-$, we get

$$|g_U V_{12}|^2 < 5 \times 10^{-19}. \tag{6}$$

Obviously, $\Sigma^+ \to p\mu^+\mu^-$ itself provides stronger constraint on the flavor changing parameter when $BR(U \to \mu^+\mu^-) \approx 1$ is assumed.

So far, we have just paid attention to the effects of Eq. (3), arising from the FCNCs at tree level via axial-vector current interactions. Next, we will introduce another interesting tensor type dipole operator which has been missed in the literature and can have significant contributions to the HyperCP data. To introduce the new type interaction for $s \to d\mu^+\mu^-$ in a model-independent way and avoid the strong constraint from $K \to \pi\mu^+\mu^-$, we first parametrize the new interaction to be a dimension-5 dipole operator, given by

$$\mathcal{L}_{T^5} = -\frac{g_{T^5}}{2\Lambda_N}\bar{d}\, i\sigma^{\mu\nu}\gamma_5 s X^0_{\mu\nu} + h.c., \tag{7}$$

where Λ_N denotes the energy scale of new physics, g_{T^5} is a dimensionless parameter and $X^0_{\mu\nu} = \partial_\mu X^0_\nu - \partial_\nu X^0_\mu$. We note that the interaction in Eq. (7) gives no contribution to $K \to \pi\mu^+\mu^-$ due to the parity conservation in strong interaction and moreover, it does

not contribute to $K_L \to \mu^+\mu^-$ either, unlike that with the axial-vector type interaction. In terms of $\langle p|\bar{d}\sigma_{\mu\nu}\gamma_5 s|\Sigma\rangle = c_\sigma \bar{p}\sigma_{\mu\nu}\gamma_5\Sigma$ and $c_\sigma = -1/3$ [3, 33], the transition matrix element for $\Sigma^+ \to pX^0$ is written as

$$M(\Sigma^+ \to pX^0) \;=\; \frac{g_{T^5}}{\Lambda_N} c_\sigma \bar{p}\, i\sigma_{\mu\nu} q^\nu \gamma_5 \Sigma\, \varepsilon^{\mu *}_{X^0}$$

and the transition amplitude square is obtained by

$$|M(\Sigma^+ \to pX_A)|^2 \;=\; 4m_\Sigma \left(g_{T^5} c_\sigma\right)^2 \left[4E_X p_p \cdot p_X - m_X^2 E_p + 3m_p m_X^2\right] .$$

Consequently, the BR for the decay chain is found to be

$$\begin{aligned} &\mathcal{B}(\Sigma^+ \to pX^0, X^0 \to \mu^+\mu^-) \\ &= 2.2 \times 10^{11} g_{T^5}^2 \left(\frac{\mathrm{GeV}}{\Lambda_N}\right)^2 \mathcal{B}(X^0 \to \mu^+\mu^-) . \end{aligned}$$

If the anomalous HyperCP events are dictated by the electric dipole operator in Eq. (7), we find

$$\left(\frac{g_{T^5}}{\Lambda_N}\right)^2 \mathcal{B}(X^0 \to \mu^+\mu^-) \;=\; \left(1.41^{+1.09}_{-0.86} \pm 0.68\right) 10^{-19} GeV^{-2} . \tag{8}$$

With $\mathcal{B}(X^0 \to \mu^+\mu^-) \approx 1$, Eq. (8) could be regarded as the bound on $g_{T^5}^2/\Lambda_N^2$ model-independently.

After analyzing the importance of the dimension-5 dipole operator, the question is how to construct a physical model to satisfy the condition in Eq. (8). In what follows, we are going to demonstrate that the new type operator in Eq. (7) could be realized in the U-boson model. Since the R-parity in our consideration is conserved, to examine the U-boson effects in the SUSY framework of models, we also need to know the couplings of the U-boson and squarks. In terms of SUSY, from Eq. (1) the interactions of the U-boson to squarks are found to be

$$\mathcal{L}_{\tilde{f}\tilde{f}U} \;=\; -ig_U \sum_f Q_f \left[\tilde{f}_R^* \overleftrightarrow{\partial}_\mu \tilde{f}_R - \tilde{f}_L^* \overleftrightarrow{\partial}_\mu \tilde{f}_L\right] U^\mu .$$

Clearly, to get the $s \to dU$ transition, we need to calculate the U-penguin diagrams illustrated in Fig. 1. In the figure, the mass insertion parameters $(\delta^d_{ij})_{LR}$ are defined by

$$(\delta^d_{ij})_{LR} \;=\; \frac{1}{m_{\tilde{q}}^2}\left(A^{d\dagger}_{ij} v_d - Y^d_{ij}\mu v_u\right) , \tag{9}$$

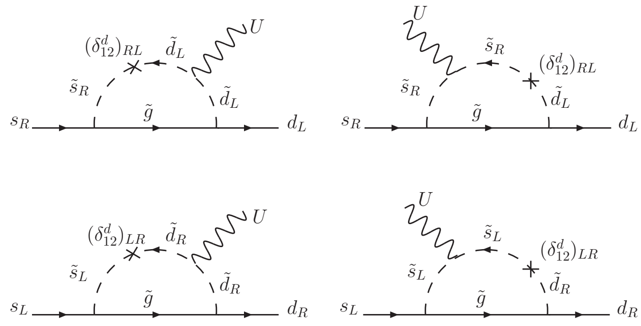

FIG. 1: U-penguin diagrams for $s \to dU$.

where $m_{\tilde{q}}$ is the average squark mass, $v_{d(u)}$ is the vacuum expectation value (VEV) of $H_{d(u)}$ and μ is the mixing parameter of H_d and H_u.

As usual, we employ the mass insertion approximation to estimate the contributions in Fig. 1 and the result is obtained to be proportional to

$$f_{sd}\bar{d}i\sigma_{\mu\nu}\left[\left(\delta^d_{12}\right)_{RL}P_R - \left(\delta^d_{12}\right)_{LR}P_L\right]sU^{\mu\nu} \tag{10}$$

with $U^{\mu\nu} = \partial^\mu U^\nu - \partial^\nu U^\mu$ and $f_{sd} = g_U(Q_s - Q_d)$. Here, the super-Cabibbo-Kobayashi-Maskawa (SCKM) basis has been adopted, *i.e.*, the squark fields have been transformed into the states that Y^d is diagonalized. In addition, the interactions for the gluino-quark-squark are taken to be

$$\mathcal{L} \;=\; -\sqrt{2}g_s\left[\bar{q}P_R\tilde{g}^aT^a\tilde{q}_L - \bar{q}P_L\tilde{g}^aT^a\tilde{q}_R\right] + h.c.\,,$$

where g_s is the strong coupling constant and T^q denotes the Gell-Mann matrices. Although the U-boson is axially coupled to quarks in the interacting eigenstates and its couplings to the left-handed and right-handed squarks are the same (opposite) in magnitude (sign), due to the misalignment between quarks and squarks in the physical states, the transition amplitudes for $s \to dU$ induced by the U-penguin diagrams involve not only electric dipole but also magnetic dipole operators. In the early analysis, we have shown that a hermitian Y^d could naturally lead to pure axial-vector couplings. Moreover, the hermiticity of Y^d also makes the A^d be nearly hermitian. Hence, by utilizing the hermiticities of Y^d and A^d, the mass insertion parameters could be simplified to be

$$(\delta^d_{12})_{RL} \approx (\delta^d_{12})_{LR}\,. \tag{11}$$

It is worth mentioning that with the same requirement, one can also find that CP asymmetries in $\Lambda \to p\pi$ decays could naturally be as large as $O(10^{-4})$ where the SM prediction is

$O(10^{-5})$ [35]. With the property in Eq. (11), the exact transition of $s \to dU$ in Eq. (10) can be written in terms of the dimension-5 operator as

$$\mathcal{L}_{dim5} = -\frac{g_5}{2m_{\tilde{g}}} \bar{d} i \sigma_{\mu\nu} \gamma_5 s U^{\mu\nu} + h.c. \tag{12}$$

where

$$g_5 = \frac{g_s^2 C_F}{16\pi^2} f_{sd} x (\delta_{12}^d)_{RL} \tag{13}$$

with $C_F = 4/3$, $x = m_{\tilde{g}}^2/m_{\tilde{q}}^2$ and $m_{\tilde{q}}$ being the gluino mass. By comparing to Eq. (7), here the new physics scale can be identified to be the SUSY breaking related scale, *i.e.* $\Lambda_N = m_{\tilde{g}}$.

We now examine the naturalness for g_5 to satisfy the limit of the HyperCP data given by Eq. (8). From Eq. (13), we see that the unknown parameters are the average gluino and squark masses, f_{sd} and $(\delta_{12}^d)_{RL}$. It is known that $(\delta_{12}^d)_{RL}$ associated with a specific value of x could be constrained by the $K^0 - \bar{K}^0$ mixing. According to the results in Ref. [34], we present the constraints in Table I. From the decays of $\eta' \to UU$ and $\eta \to UU$, we can

TABLE I: The constraints on $(\delta_{12}^d)_{RL}$ by Δm_K with $m_{\tilde{q}} = 500$ GeV and $x = m_{\tilde{g}}^2/m_{\tilde{q}}^2$ being 0.3, 1.0 and 4.0, respectively [34].

x	0.3	1.0	4.0
$(\delta_{12}^d)_{RL}$	7.9×10^{-3}	4.4×10^{-3}	5.3×10^{-3}

get the direct constraints for $f_s = g_U Q_s$ and $f_d = g_U Q_d$ to be $< 5 \times 10^{-2}$ and 3.18×10^{-2}, respectively [19], which lead to $f_{sd} = f_s - f_d < 3 \times 10^{-2}$. Since the direct constraints on the parameters are looser, we take f_{sd} as a free parameter to fit the HyperCP data. However, it is clear that with a small value of g_5 as the one in Eq. (6), the effect of Eq. (12) will disappear. With $m_{\tilde{q}} = 500$ GeV, the value of g_5^2 as a function of f_{sd} is presented in Fig. 2. From the results, we see clearly that the dimension-5 operator induced by the U-boson in supersymmetric models also provides a plenty of allowed space (the band in Fig. 2) for the HyperCP data. Explicitly, with $f_{sd} \sim 2.5 \times 10^{-3}$ and $x \sim 1$, we obtain $g_5^2/m_{\tilde{g}}^2 \sim 10^{-19}$ GeV^{-2} which is within the model-independent constraint shown in Eq. (8).

In summary, we have studied the scenario of the very light gauge U-boson which weakly couples to fermions in the framework of SUSY with one extra $U(1)'$ gauge symmetry [16]. We have shown that the spin-1 U-boson can be a good candidate of the new light particle

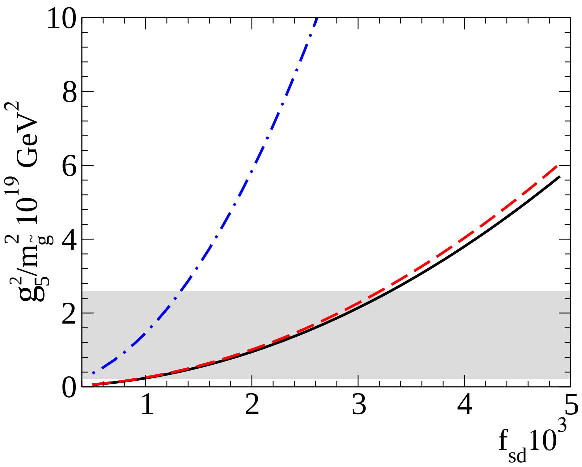

FIG. 2: $g_5^2/m_{\tilde{g}}^2$ as a function of f_{sd}, where the solid, dashed and dot-dashed lines denote $x = 0.3$, 1.0 and 4.0, respectively, and the band is the HyperCP data with 1σ errors.

suggested by the HyperCP experiment. In the model, we have found that the FCNCs for the HyperCP events in the decay of $\Sigma^+ \to p\mu^+\mu^-$ can be generated at both tree and loop levels. In particular, we have pointed out that the loop induced $s \to dU$ transition, involving the tensor-type interaction with the dimension-5 electric dipole operator, plays a very important role on the HyperCP data. This interaction has not been investigated previously in the literature as it gives no contributions to $K_L \to \mu^+\mu^-$ and $K \to \pi\mu^+\mu^-$. Finally, we remark that the contributions from Eqs. (3) and (12) to $\Sigma^+ \to pe^+e^-$ are negligible in comparison with that in the SM [3]. The study of the tensor interaction has an impact on the decay of $K_L \to \gamma\mu^+\mu^-$ and similar discussions can be also generalized to B and τ decays [8]. Our explanation of the HyperCP events with the spin-1 U-boson is clearly different from that based on a light spin-0 pseudoscalar Higgs boson in Ref. [5] or a light sgoldstino in Ref. [6]. In particular, we emphasize that the U-boson can involve a rich phenomenology in particle physics as well as cosmology [15, 16, 17, 18, 19, 20, 21, 22, 23].

Acknowledgments

This work is supported in part by the National Science Council of R.O.C. under Grant #s:NSC-95-2112-M-006-013-MY2, NSC-95-2112-M-007-059-MY3 and NSC-96-2112-M-033-

003-MY3.

---

[1] H. Park *et al.* (HyperCP Collaboration), Phys. Rev. Lett. **94**, 021801 (2005).

[2] L. Bergström, R. Safadi, and P. Singer, Z. Phys. C**37**, 281 (1988).

[3] X.G. He, J. Tandean, and G. Valencia, Phys. Rev. D**72**, 074003 (2005).

[4] D.M. Kaplan, arXive:0707.1543 [hep-ex].

[5] X.G. He, J. Tandean, and G. Valencia, Phys. Rev. D**74**, 115015 (2006); Phys. Rev. Lett. **98**, 081802 (2007).

[6] D. S. Gorbunov and V. A. Rubakov, Phys. Rev. D **64**, 054008 (2001); Phys. Rev. D**73**, 035002 (2006); S. V. Demidov and D. S. Gorbunov, JETP Lett. **84**, 479 (2007).

[7] X.G. He, J. Tandean, and G. Valencia, Phys. Lett. B**631**, 100 (2005).

[8] C.H. Chen and C.Q. Geng, Phys. Lett. B**645**, 189 (2007).

[9] N.G. Deshpande, G. Eilam, and J. Jiang, Phys. Lett. B**632**, 212 (2006); C.Q. Geng and Y.K. Hsiao, Phys. Lett. B**632**, 215 (2006).

[10] S. L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D**2**, 1285 (1970).

[11] C. H. Chen and C. Q. Geng, Phys. Rev. D**66**, 014007 (2002) [arXiv:hep-ph/0205306]; C. H. Chen and C. Q. Geng, JHEP **10**, 053 (2006) [arXiv:hep-ph/0608166].

[12] R.N. Mohapatra and G. Senjanovic, Phys. Lett. B**79**, 283 (1978).

[13] S. Chaudhuri, S. W. Chung, G. Hockney and J. D. Lykken, Nucl. Phys. B **456**, 89 (1995); G. Cleaver, M. Cvetic, J. R. Espinosa, L. L. Everett and P. Langacker, Nucl. Phys. B **525**, 3 (1998); G. Cleaver, M. Cvetic, J. R. Espinosa, L. L. Everett, P. Langacker and J. Wang, Phys. Rev. D **59**, 115003 (1999).

[14] P. Langacker and M. Plümacher, Phys. Rev. D**62**, 013006 (2000); D.A. Demir, G.L. Kane, and T.T. Wang, Phys. Rev. D**72**, 015012 (2005); C.H. Chen and H. Hatanaka, Phys. Rev. D**73**, 075003 (2006); X.G. He and G. Valencia, arXiv:hep-ph/0703270.

[15] P. Fayet, Phys. Lett. B**69**, 489 (1977); **70**, 461 (1977).

[16] P. Fayet, Phys. Lett. B**95**, 285 (1980).

[17] C. Boehm and P. Fayet, Ncul. Phys. B**683**, 219 (2004); P. Fayet, Phys. Rev. D**70**, 023514 (2004); C. Bouchiat and P. Fayet, Phys. Lett. B**608**, 87 (2005).

[18] P. Jean *et al.*, Astron. Astrophys. **407**, L55 (2003); C. Boehm *et al.*, Phys. Rev. Lett. **92**,

101301 (2004); C. Boehm, P. Fayet, and J. Silk, Phys. Rev. D**69**, 101302 (2004).

[19] P. Fayet, Phys. Rev. D**74**, 054034 (2006).

[20] P. Fayet, Phys. Rev. D**75**, 115017 (2007).

[21] S.H. Zhu, Phys. Rev. D**75**, 115004 (2007).

[22] S.N. Gninenko and N.V. Krasnikov, Phys. Lett. B**427**, 307 (1998); Phys. Lett. B**513**, 119 (2001).

[23] B. A. Dobrescu, Phys. Rev. Lett. **94**, 151802 (2005); B. A. Dobrescu and I. Mocioiu, JHEP **0611**, 005 (2006).

[24] S. Abel *et al.*, Phys. Lett. B**504**, 241 (2001); S. Abel, S. Khalil, and O. Lebedev, Phys. Rev. Lett. **89**, 121601 (2002).

[25] R.N. Mohapatra and G. Senjanovic, Phys. Lett. B**79**, 283 (1978); R.N. Mohapatra and A. Rasin, Phys. Rev. Lett. **76**, 3490 (1996); Phys. Rev. D**54**, 5835 (1996); K.S. Babu, B. Dutta and R. N. Mohapatra, Phys. Rev. D**61**, 091701 (2000).

[26] H. Fritzsch, Phys. Lett. B**70**, 4361 (1977).

[27] C. Jarlskog, Phys. Rev. Lett. **55**, 1039 (1985); Z. Phys. C **29**, 491 (1985);

[28] P.H. Frampton and C. Jarlskog, Phys. Lett. B**154**, 421 (1985).

[29] T.P. Cheng and L.F. Li, Phys. Rev. Lett. **55**, 2249 (1985); Phys. Rev. D**34**, 219 (1986).

[30] K. Matsuda and H. Nishiura, Phys. Rev. D**74**, 033014 (2006).

[31] J. P. Leveille, Nucl. Phys. B **137**, 63 (1978).

[32] Particle Data Group, W.M. Yao *et al.*, J. Phys. G: Nucl. Part. Phys. **33**, 1 (2006).

[33] J.F. Donoghue, E. Golowich, and B.R. Holstein, Dynamics of the Standard Model (Cambridge University Press, Cambridge, 1992).

[34] F. Gabbiani *et al.*, Nucl.Phys. B**477**, 321 (1996).

[35] C.H. Chen, Phys. Lett. B**521**, 315 (2001).